Technical Report

Disruption Mitigation Using High Pressure Gas Jets (DE-FG02-04ER54762)

Principal Investigator: Dennis Whyte, *University of Wisconsin – Madison**

Period of activity: Feb. 2004 – Feb. 2007

Overview

The goal of this research is to establish credible disruption mitigation scenarios based on the technique of massive gas injection. Disruption mitigation seeks to minimize or eliminate damage to internal components that can occur due to the rapid dissipation of thermal and magnetic energy during a tokamak disruption. In particular, the focus of present research is extrapolating mitigation techniques to burning plasma experiments such as ITER, where disruption-caused damage poses a serious threat to the lifetime of internal vessel components.

A majority of effort has focused on national and international collaborative research with large tokamaks: DIII-D, Alcator C-Mod, JET, and ASDEX Upgrade. The research was oriented towards empirical trials of gas-jet mitigation on several tokamaks, with the goal of developing and applying cohesive models to the data across devices.

The attached Bibliography lists publication and reports stemming from the cross-device collaborative research and demonstrates the high productivity of the three-year research period:

- 20 peer-reviewed journal articles,
- 6 invited talks,
- Over 10 plenary and contributed talks and posters.

Major Findings & Research Highlights

Here we summarize the major findings of the research activity. We refer the reader to the cited scientific articles in the Bibliography for details of the research.

1. Massive gas injection was shown to be effective for disruption mitigation on the Alcator C-Mod tokamak [Whyte JNM07, Granetz NF07, Greenwald 05]. Mitigation was successful at the ITER magnetic field, plasma pressure and energy density, an important empirical demonstration. The gas injection was shown to:

   a. Invoke an efficient radiative dissipation of the plasma thermal energy, particularly with argon gas injection
   b. Significantly reduce thermal loads on the divertor.
   c. Reduce halo currents by about a factor of two.
   d. Not produce runaway electrons despite the rapid current quench and high electric field.

2. Collaborative studies on gas-plasma interactions between DIII-D and C-Mod indicated that MHD plays a dominant role in bringing the injected impurities into the core plasma, rather than ballistic neutral penetration of the gas [Hollmann NF04, Granetz NF 07]. This is overall a positive result since by invoking the plasma's own instability, one eases technological restrictions for the required gas pressure on high temperature/pressure ITER plasmas. However it also introduces more uncertainty to predicting the thermal quench evolution in ITER. Modeling and experiments were carried out towards improving knowledge of the MHD-induced transport. The MHD evolution of C-Mod results was modeled using the non-ideal resistive MHD numerical model, NIMROD, reproducing many of the features of the C-Mod experiments [Izzo IAEA06]. This was empirically supported with DIII-D experiment that showed the dependence of the thermal quench duration on the radial position of the q=2 surface [Hollmann POP07].

3. Significant testing, extension and utilization of the KPRAD code and methodology for studying disruption mitigation. KPRAD is a numerical code that self-consistently evolves the ionization and radiation balance of the highly perturbing impurities in the plasma.

   a. The current quench duration of C-Mod was accurately predicted by KPRAD for the different noble gases injected [Whyte JNM07]. This was a rigorous test for KPRAD in that the size and current density of C-Mod are substantially different from DIII-D, where KPRAD was first developed by D. Whyte. Most importantly this success indicates that with sufficient impurity density, the atomic physics of the injected species will dictate the current quench rate for a given target plasma current and size. This is consistent with cross-device comparisons as well [Lipshcultz NF07]. This bodes well for "tailoring" the ITER current quench induced by gas injection to the desired rate by species selection of the injected gas.

b. The radiation and atomics physics package of KPRAD was "ported" into the MHD NIMROD code to effectively make a new code, NIMRAD [Izzo IAEA06]. This seemed necessary given the coupled nature of the radiation-induced plasma pressure changes and the invoked MHD, which in turn affects the impurity transport. Preliminary NIMRAD results showed that the inclusion of self-consistent radiation physics showed important differences between He and Ar gas injection that were qualitatively similar to experimental differences seen in C-Mod.

c. The KPRAD code was also ported to the MATLAB language so that it could be coupled with the analytical halo current model and thus examine the coupled roles of plasma cooling and current profile evolution [Humphreys EPS06], and important step toward predictive modeling of halo current evolution in ITER [Humphreys IAEA06].

4. It was found that the previously ignored bremsstrahlung radiation losses play an important limiting role in setting runaway electron energy during the current quench in ITER [Bakhtiari PoP05].

5. The role of neutrals in setting plasma resistivity, and hence current quench duration, following a massive gas injection were studied self-consistently using an analytic resistivity model and KPRAD [Bakhtiari PoP06]. It was found that for relative neutral fractions expected in disruption mitigation that the neutrals did not significantly alter the effective plasma resistivity.

6. Contributors on disruption physics and mitigation for the ITER Tokamak Physics Basis Update [Hender 06], and specific research on disruption predictions for ITER [Sugihara IAEA04].

7. The role of intrinsic wall fluxes in setting impurity and fuelling in unmitigated disruptions was investigated on DIII-D [Gray 04, Hollmann EPS04]. It was found that high density "natural" disruptions in fact tended to "self-mitigate" by releasing large amounts of carbon and fuel from the walls.

8. KPRAD and thermal modeling showed that even an *ideal* mitigation on ITER, i.e. when all the plasma energy is dissipated uniformly by radiation, that the radiation flash could produce significant amounts (10-100 kg) of molten beryllium at the first wall of ITER [Whyte JNM05]. The fate of the layer depends on complex MHD, but the simultaneous loss of diamagnetic current in the plasma in general tends to destabilize the Be molten film. The consequences of this melt production are uncertain but a concern for ITER.

9. A review paper on disruption physics and mitigation on DIII-D was published [Whyte FST05].

10. A novel technique to recover tritium in ITER was proposed and developed. The method is based on rapid radiative heating of plasma-viewing surfaces by planned radiative terminations using high-pressure gas injection [Whyte JNM05]. The study showed that low current ITER plasmas has sufficient energy density to invoke significant tritium recovery from PFC surfaces, without damaging the underlying components. This is a promising non-invasive tritium recovery technique for ITER. Preliminary tests on using disruptions for fuel recovery were positive on Alcator C-Mod [Whyte IAEA06].

11. Empirical comparison of thermal quench and current quench durations across ASDEX Upgrade, DIII-D and Alcator C-Mod following massive gas injection [Lipschultz NF07]. The thermal quench duration roughly scaled as the device size and

inversely as the sound speed of the injected gas one the injected gas density reached a minimum value. This is possibly a positive result for ITER in that one expects slower thermal quenched given its large size, however data from other devices, particularly JET is required for a more certain extrapolation to ITER.

Conclusions

Disruption mitigation using gas jet injection has proven to be a viable candidate for avoiding or minimizing damage to internal components in burning plasma experiments like ITER. The physics understanding is progress towards a technological design for the required gas injection system in ITER.

Bibliography

<u>Publications and reports resulting from research activity supported with</u>

<u>US DOE Grant No DE-FG02-04ER54762 (2004-2007)</u>

Alphabetical order by first author

<u>Publications</u>

1. [Bakhtiari PoP05]
M. Bakhtiari, G.J. Kramer, and D.G. Whyte, "*Momentum-space study of the effect of bremsstrahlung radiation on the energy of runaway electrons in tokamaks*", Physics of Plasmas **12** 1025031-1025035 (2005).

2. [Bakhtiari PoP06]
M. Bakhtiari, D.G. Whyte, "*Time-dependent analysis of the resistivity of post-disruption tokamak plasmas*," Physics of Plasmas **13** 112511 (2006).

3. [Granetz NF06]
R. Granetz, D.G. Whyte, V.A. Izzo, T. Biewer, M.L. Reinke, J. Terry, A. Bader, M. Bakhtiari, T. Jernigan, G. Wurden, "*Gas jet disruption mitigation studies on Alactor C-Mod*, " Nuclear Fusion **26** 1001-1008 (2006).

4. [Granetz NF07]
R.S. Granetz, E.M. Hollmann, D.G. Whyte, V.A. Izzo, G.Y. Antar, A. Bader, M. Bakhtiari, T. Biewer, J.A. Boedo, T.E. Evans, T.C. Jernigan, D.S. Gray, M. Groth, D.A. Humphreys, C.J. Lasnier, R.A. Moyer, P.B. Parks, M.L. Reinke, D.L. Rudakov, E.J. Strait, J.L. Terry, J. Wesley, W.P. West, G. Wurden, J. Yu, "*Gas Jet Disruption Mitigation Studies on Alcator C-Mod and DIII-D*." Nuclear Fusion **47** 1086-1091 (2007)..

5. [Gray 04]
D.S. Gray, S.C. Luckhardt, L. Chousal, G. Gunner, A.G. Kellman, and D.G. Whyte, "*Time resolved radiated power during tokamak disruptions and spectral averaging of AXUV photodiode response in DIII-D*", Review of Scientific Instruments **75** 376-381 (2004).

6. [Greenwald 05]

M. Greenwald, D. Andelin, N. Basse, S. Bernabei, P. Bonoli, B. Bose, C. Boswell, R. Bravenec, B. Carreras, I. Cziegler, E. Edlund, D. Ernst, C. Fasoli, M. Ferrara, C. Fiore, R. Granetz, O. Grulke, T. Hender, J. Hosea, D.H. Howell, A. Hubbard, J. Hughes, I. Hutchinson, A. Ince-Cushman, J. Irby, B. LaBombard, R. LaHaye, L. Lin, Y. Lin, B. Lipschultz, J. Liptac, S. Lisgo, A. Lynn, E. Marmar, K. Marr, D.R. Mikkelsen, R. McDermott, D. Mossessian, A. Parisot, R. Parker, C. Phillips, P. Phillips, M. Porkolab, M. Redi, J. Rice, W. Rowan, M. Sampsell, G. Schilling, S. Scott, J.T. Scoville, N. Smick, J. Snipes, P. Stangeby, V. Tang, J. Terry, M. Ulrickson, G. Wallace, D. Whyte, J. Wilson, J. Wright, S. Wolfe, S. Wukitch, B. Youngblood, H. Yuh, K. Zhurovich, and S. Zweben, "*Overview of the Alcator C-Mod program*", Nuclear Fusion **45** 109-117 (2005).

7. [Hender 06]
T.C. Hender, J. Wesley, J. Bialek, A. Bondeson, A.H. Boozer, R.J. Buttery, A.Garofalo, T.P Goodman, R.S. Granetz, Y. Gribov, O. Gruber, M. Gryaznevich, G. Giruzzi, S. Günter, N. Hayashi, P Helander, C.C. Hegna, D.F. Howell, D.A. Humphreys, G.T.A. Huysmans, A.W. Hyatt, A. Isayama, S.C. Jardin, Y. Kawano, A. Kellman, C. Kessel, H.R. Koslowski, R.J. La Haye, E. Lazzaro, Y.Q. Liu, V. Lukash, J. Manickam, S. Medvedev, V. Mertens, S.V. Mirnov, Y. Nakamura, G. Navratil, M. Okabayashi, T. Ozeki, R. Paccagnella, G. Pautasso, F. Porcelli, V. Pustovitov, V. Riccardo, M. Sato, O. Sauter, M.J. Schaffer, M. Shimada, P. Sonato, E.J. Strait, M. Sugihara, M. Takechi, A.D. Turnbull, E. Westerhof, D.G. Whyte, R. Yoshino, H. Zohm , and the ITPA MHD, Disruption and Magnetic Control Topical Group, "*Chapter 3*: *MHD stability, operation limits and disruptions*," Nuclear Fusion, Special Issue "Progress in the ITER Physics Basis," **47** S128-S202 (2007).

8. [Hollmann EPS04]
E.M. Hollmann, D.S. Gray, N.H. Brooks, T.E. Evans, D.A. Humphreys, C.J. Lasnier, S.C. Luchkhardt, A.G. McLean, R.A. Moyer, D.L. Rudakov, E.J. Strait, W.P. West, D.G. Whyte, "*Observation of main-chamber heat loads during disruptions in DIII-D*," Proceedings 31st European Physical Society Conference On Controlled Fusion and Plasma Physics, London, UK, June 2004, **P-2.182** (2004).

9. [Hollmann NF05]
E.M. Hollmann, T.C. Jernigan, M. Groth, D.G. Whyte, D.S. Gray, M.E. Austin, B.D. Bray, D.P. Brennan, N.H. Brooks, T.E. Evans, D.A. Humphreys, C.J. Lasnier, R.A. Moyer, A.G. McLean, P.B. Parks, V. Rozhansky, D.L. Rudakov, E.J. Strait, and W.P. West, "*Measurements of impurity and heat dynamics during noble gas jet-initiated fast plasma shutdown for disruption mitigation in DIII-D*", Nuclear Fusion **45** 1046-1055 (2005).

10. [Hollmann EPS06]
E.M. Hollmann, T.C. Jernigan, G. Antar, M. Bakhtiari, J.A. Boedo, S.K. Combs, T.E. Evans, D.S. Gray, M. Groth, D.A. Humphreys, C.J. Lasnier, R.A. Moyer, P.B. Parks, D.L. Rudakov, E.J. Strait, J.C. Wesley, W.P. West, D.G. Whyte, J. Yu, "*DIII-D studies of massive gas injection fast shutdowns for disruption mitigation,*" 33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol. **30I**, P-5.136 (2006).

11. [Hollmann POP07]
E.M. Hollmann, T.C. Jernigan, E.J. Strait, G. Antar, T.E. Evans, D.S. Gray, M. Groth, D.A. Humphreys, P.B. Parks, D.G. Whyte, "*Observation of q-profile dependence in noble gas injection radiative shutdown times in DIII-D*," Physics of Plasmas **14**, 012502 (2007).

12. [Humphreys EPS06]
D.A. Humphreys, D.G. Whyte, M. Bakhtiari, R.D. Deranian, E.M. Hollmann, A.W. Hyatt, T.C. Jernigan, A.G. Kellman, P.B. Parks, "*Predictive modeling of plasma halo evolution in post-thermal quench disruption plasmas*," 33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-5.137 (2006).

13. [Humphreys IAEA06]
D.A. Humphreys, J.R. Ferron, M. Bakhtiari, J.A. Blair, Y. In, G.L. Jackson, H.Jhang, R.D. Johnson, J.S. Kim, R.J. LaHaye, J.A. Leuer, B.G. Penaflor, E. Schuster, M.L. Walker, H. Wang, A.S. Welander, D.G. Whyte, "*Development of ITER-relevant plasma control solutions at DIII-D*," Proceedings of the 21st IAEA Fusion Energy Conference, Chengdu, China, October 2006, **TH/P3-15** Submitted to Nuclear Fusion (2006).

14. [Izzo IAEA06]
V.A. Izzo , R.S. Granetz , D.G. Whyte , M. Bakhtiari "*MHD Simulations for Studies of Disruption Mitigation by High Pressure Noble Gas Injection*," Proceedings of the 21st IAEA Fusion Energy Conference, Chengdu, China, October 2006, **TH/P3-15** (2006).

15. [Lipschultz NF07]
B. Lipschultz, X. Bonnin, A. Kukushkin, A. Leonard, J. Roth, E. Tsitrone, D. Whyte, N. Asakura, D. Coster, G. Counsell, R. Doerner, R. Dux, G. Federici, M. Fenstermacher, W. Fundamenski, P. Ghendrih, A. Herrmann, J. Hu, A. Kallenbach, S. Krasheninnikov, K. Krieger, G. Kirnev, A. Kreter, V. Kurnaev, B. LaBombard,

S. Lisgo, A. Loarte, T. Nakano, R. Neu, N. Ohno, H. Pacher, J. Paley, Y. Pan, G. Pautasso, V. Philipps, R. Pitts, V. Riccardo, V. Rohde, D. Rudakov, P. Stangeby, S. Takamura, T. Tanabe, Y. Yang, S. Zhu, "*Plasma-surface interaction, scrape-off layer and divertor physics: Implications for ITER*," ." Nuclear Fusion **47** 1189-1205 (2007).

16. [Sugihara IAEA04]
M. Sugihara, V. Lukash, Y. Kawano, R. Khayrutdinov, N. Miki, A. Mineev, J. Ohmori, H. Ohwaki, D. Humphreys, A. Hyatt, V. Riccardo, D. Whyte, V. Zhogolev, P. Barabaschi, Yu. Gribov, K. Ioki, M. Shimada, "*Analysis of disruption scenarios and their possible mitigation in ITER,*" Proceedings of the 20th IAEA Fusion Energy Conference, Vilamoura, Portugal, November 2004, **IT/P3-29** (2004).

17. [Whyte JNM05]
D.G. Whyte and J.W. Davis, "*Tritium recovery in ITER by radiative plasma terminations*", Journal of Nuclear Materials **337-339** 560-564 (2005).

18. [Whyte FST05]
D.G. Whyte, D.A. Humphreys, and A.G. Kellman, "*Disruption physics and mitigation on DIII-D*", Fusion Science and Technology **48** 954-967 (2005).

19. [Whyte IAEA06]
D.G. Whyte, B. Lipschultz, J. Irby, R. Granetz , B. LaBombard, J. Terry, G.M. Wright, "*Hydrogenic Fuel Recovery and Retention with Metallic Plasma-Facing Walls in the Alcator C-Mod Tokamak*," Proceedings of the 21st IAEA Fusion Energy Conference, Chengdu, China, October 2006, **EX/P4** (2006).

20. [Whyte JNM07]
D.G. Whyte, R. Granetz, M. Bakhtiari, V. Izzo, T. Jernigan, J. Terry, M. Reinke, B. Lipschultz, "*Disruption mitigation on Alcator C-Mod using high-pressure gas injection: Experiments and modeling toward ITER*," Journal of Nuclear Materials **363-365** 1160-1167 (2007).

Reports

1. [Whyte UW05]
D.G. Whyte, M. Bakhtiari, "Scoping study of a fast DIII-D VDE disruption using KPRAD to predict L/R current quench times," University of Wisconsin – Madison Memo, July 12, 2005 (2005).

2. [Whyte ITERtask06]
D.G. Whyte, "*Disruptions and their mitigation on ITER*," U.S. ITER physics task report, November 2006 (2006).

Invited Talks

1. D.G. Whyte, et al. "*Gas jet disruption mitigation studies*," 33rd European Physical Society Conference on Plasma Physics, Rome, June 2006.

2. D.G. Whyte, et al. "*Beryllium walls and tritium recovery: Issues arising from radiative disruption mitigation in JET*," JET Beryllium Wall Workshop, UKAEA Abingdon UK, October 2003.

3. D.G. Whyte, et al. "*The challenges of material walls and boundary plasmas in magnetic fusion energy*," keynote address to the Netherlands NNV/CPS Symposium on Plasma Physics, Lunteren, Netherlands, March 2005.

4. R. Granetz, D. Whyte, et al. "*Gas jet disruption mitigation studies on Alcator C-Mod*," 47th Meeting of the American Physical Society Division of Plasma Physics, Denver CO, October 2005.

5. D.G. Whyte, et al. "*Disruptions*" US Burning Plasma Organization Workshop, Oak Ridge, TN, December 2005.

6. D.G. Whyte "*Disruption mitigation on Alcator C-Mod with high-pressure gas jets*," Workshop on Active Control of MHD, Madison WI, November 2005.

Plenary Talks & Colloquia

1. D.G. Whyte, "*Tritium recovery in ITER by radiative plasma terminations*", Plenary talk, 16th International Conference on Plasma-Surface Interactions in Controlled Fusion Devices, Portland, Maine USA May 2004.

2. D.G. Whyte, "*Disruption mitigation on Alcator C-Mod using high-pressure gas injection:* Experiments *and modeling toward ITER*," Plenary talk, 17th International Conference on Plasma-Surface Interactions in Controlled Fusion Devices, Hefei, China, May 2006

3. D.G. Whyte "*Disruption mitigation and tritium retention in ITER: Progress and challenges*," Colloquium, Department of Applied Physics and Applied Mathematics, Columbia University, New York NY, October 2006.

Contributed Papers, Posters & Talks

1. M. Bakhtiari, R. Granetz, V. Izzo, D.G. Whyte, M. Reinke, K. Zhurovich, "Using mixed gases for massive gas injection disruption mitigation on Alcator C-Mod," Bulletin of the American Physical Society 48th Annual Meeting of the Division of Plasma Physics, October 30 – November 3 2006, Philadelphia PA, *J01.00006* (2006).

2. R. S. Granetz, S.M. Wolfe, V.A. Izzo, M.L. Reinke, J.L. Terry, J.W. Hughes, K. Zhurovich, D.G. Whyte, M. Bakhtiari, G. Wurden, "Real-time sensing and gas jet mitigation on Alcator C-Mod," Bulletin of the American Physical Society 48th Annual Meeting of the Division of Plasma Physics, October 30 – November 3 2006, Philadelphia PA, *QP1.00054* (2006).

3. V.A. Izzo, R.S. Granetz, D.G. Whyte, M. Bakhtiari, "Simulations of gas jet disruption mitigation," Bulletin of the American Physical Society 48th Annual Meeting of the Division of Plasma Physics, October 30 – November 3 2006, Philadelphia PA, *J01.00005* (2006).

4. E.M. Hollmann, G. Antar, J. Boedo, R.A. Moyer, D.L. Rudakov, J. Yu, T.C. Jernigan, S. Combs, T.E. Evans, D.A. Humphreys, P.B. Parks, E.J. Strait, J.C. Wesley, M. Groth, M. Bakhtiari, D.G. Whyte, "DIII-D studies of massive gas injection for disruption mitigation," Bulletin of the American Physical Society 48th Annual Meeting of the Division of Plasma Physics, October 30 – November 3 2006, Philadelphia PA, *UP1.00019* (2006).

5. M. Bakhtiari, D.G. Whyte, P.B. Parks, "Study of the transient gas flow through tubes applicable to disruption mitigation," Bulletin of the American Physical Society 47th Annual Meeting of the Division of Plasma Physics, October 24 – 28 2005, Denver CO, *BP1.00014* (2005).

6. V. A. Izzo, R.S. Granetz, D.G. Whyte, M. Bakhtiari, "Simulations of disruption mitigation by high-pressure gas jet on Alcator C-Mod," Bulletin of the American Physical Society 47th Annual Meeting of the Division of Plasma Physics, October 24 – 28 2005, Denver CO, *KP1.00008* (2005).

7. D.G. Whyte, M. Bakhtiari, R.S. Granetz, V. Izzo, J. Terry, B. Lipschultz, T. Jernigan, "Disruption studies on C-Mod: Mitigation & hydrogen/deuterium fuel recovery," Bulletin of the American Physical Society 47th Annual Meeting of the Division of Plasma Physics, October 24 – 28 2005, Denver CO, *RO3.00005* (2005).

8. D.G. Whyte, J.W. Davis “Tritium recovery in ITER by radiative plasma terminations,” Bulletin of the American Physical Society 46th Annual Meeting of the Division of Plasma Physics, November 15-19 2004, Savannah GA, *CP1.033* (2004).

9. D. Whyte, E. Hollmann, R. Granetz, T. Jernigan, V. Izzo, G. Antar, M. Bakhtiari, J. Terry, P.B. Parks, “DIII-D & Alcator C-Mod disruption mitigation,” ITPA Meeting, MHD Topical Group, July 4-7, 2005 Tarragona, Spain (2005).

10. D. Whyte, “Beryllium melt layer stability with radiative disruption mitigation,” ITPA Meeting, SOL/Divertor Topical Group, July 4-7, 2005 Tarragona, Spain (2005).